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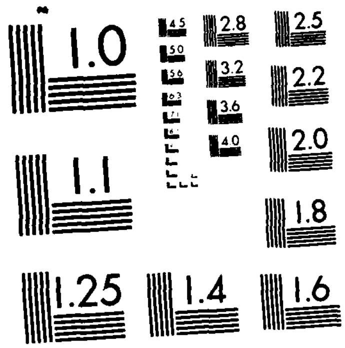
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COMPRESSION OF RUBBER LAYERS BONDED BETWEEN TWO PARALLEL RIGID CYLINDERS OR BETWEEN TWO RIGID SPHERES

by

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An approximate theoretical treatment is presented for small compressions of a rubber layer bonded between two opposed curved rigid surfaces, cylindrical or spherical in shape. The deformation is treated in two parts: a simple compression; and shearing deformations necessary to maintain zero slip at the bonded surfaces. Forces and hydrostatic pressures due to the second deformation are found to be the major terms for thin layers. Predicted compression stiffnesses are compared with measured values for various initial separations

1. Introduction

The stiffness of bonded rubber blocks under small compressive deformations has been studied extensively. A recent review deals with the problem in connection with the use of elastomeric laminates as bridge bearings (1). However, previous studies have been mainly concerned with a flat rubber block bonded between two flat rigid plates. An approximate treatment is given here for the stiffness of a rubber layer bonded between two opposed curved rigid surfaces, cylindrical or spherical in shape (Figure 1). The predictions of the theoretical treatment are then compared with measured values of compressive stiffness for various initial separations (and hence rubber layer thicknesses) of the two rigid surfaces, relative to their diameter.

2. Theoretical considerations

The analysis follows that of Gent and Meinecke (2), treating the total compressive force F necessary to bring about a small compressive displacement δ as consisting of two parts: F_1 arising from a simple compression of the rubber and F_2 arising from the restraints at the bonded surfaces. Thus, the compression stiffness $K(=F/\delta)$ is given by

$$K = K_1 + K_2 \tag{1}$$

where $K_1 = F_1/\delta$, $K_2 = F_2/\delta$.

The calculation of K_1 merely involves the integration of compressive stresses on the assumption that the rubber is not bonded to the curved surfaces and hence undergoes a simple compression. Details are given in Appendix 1. The results are

$$3K_1/4LE = AI - \pi/2 \tag{2}$$

for a layer compressed between two long rigid cylinders of length L and diameter D, where E is Young's modulus of the rubber. The term A represents

$$A = 1 + (h/D), \tag{3}$$

where h denotes the separation of the cylinders, and

$$I = [2/(A^2 - 1)^{1/2}]\tan^{-1}[(A^2 - 1)^{1/2}/(A - 1)]. \tag{4}$$

For a layer compressed between two rigid spheres of diameter D,

$$K_1/DE = (\pi/2)\{A \ln[A/(A - 1)] - 1\}. \tag{5}$$

The terms K_1 are relatively small in comparison with the terms K_2 when the rigid surfaces are close together and the rubber layer is thin at its center. Computation of K_2 is difficult, however. The stresses in the interior of a bonded rubber block are complex. For simplicity, they are replaced here by a hydrostatic pressure P, which is a function only of the lateral distance x of the point in question from the central axis. This simple stress system can be maintained only if the deformation takes a particularly simple form, in which horizontal planes in the undeformed material remain plane in the deformed state and originally-vertical planes become parabolic displacement fronts in the compressed state.

This simple deformation regime has been assumed to hold previously for rubber blocks compressed between flat parallel plates (2), and it appears to be satisfactory, except near the free surface, when the block is thin (3). In the present case, it will clearly be invalid away from the center of the layer, but the contribution of rubber in these regions to the total compressive force will be small anyway. The assumption is retained, therefore, in order to calculate the extent of lateral bulging, shown schematically in Figure 2, and the corresponding shear deformations which are maintained by the internal pressure P.

Details are given in Appendix 2. The results for the maximum pressure P_m when $x = 0$ and the stiffness component K_2 are as follows for a layer compressed between two rigid cylinders

$$K_2/LE = (\pi/2) + (1/2A) - A[(2A^2 - 3)I - 1]/2\,(A^2 - 1), \tag{6}$$

where A and I are given by equations 3 and 4, and

$$P_m D/E\delta = 1/\,2A(A - 1)^2 \,. \tag{7}$$

For a block compressed between two rigid spheres:

$$K_2/DE = (\pi/8)[3 + (1/2A) + \{1/(A - 1)\} + 3A\,\ell n\{1 - (1/A)\}] \tag{8}$$

and

$$P_m D/E\delta = 1/4A(A - 1)^2 \tag{9}$$

Values of $\underline{K_1}$ and $\underline{K_2}$, given by equations 2 and 6 for an elastic layer bonded between two rigid cylinders and by equations 5 and 8 for an elastic layer bonded between two rigid spheres, provide theoretical estimates of the compression stiffness, equation 1. They are compared below with experimentally-measured values of compression stiffness for layers of a silicone elastomer of varied thickness $\underline{h}$, bonded between two long rigid cylinders or two rigid spheres.

3. Experimental details

(i) Preparation of test specimens.

Test specimens were prepared using a castable silicone rubber formulation (Sylgard S-184, plus 10 percent of Sylgard C-184 crosslinking agent, both supplied by Dow Corning Corporation). The mixture was degassed under vacuum for 30 min and then poured into the mold cavity and cured for 24 h at 80° C.

Molds were prepared using thick Mylar film to contain the silicone rubber formulation in the gap between two stainless steel tubes, placed parallel to each other, or between two glass spherical flasks. The steel tubes were 127 mm long and 19.0 mm in external diameter. The glass flasks had an external diameter of 41.7 mm. Specimens were prepared with various spacings in the range 2 - 30 mm.

Before use, the steel cylinders and glass flasks were thoroughly cleaned and coated with a primer (92-023 primer, Dow Corning Corporation) to secure good bonding to the silicone rubber compound.

(ii) Measurement of compression stiffness.

Force-displacement relations were determined in compression, using an Instron test machine to apply the loads and cathetometers to measure the corresponding deflections. Values of compression stiffness were then given by the initial slopes of the force-displacement relations.

In a separate experiment, using a a cast bar of the same rubber compound under small tensile deformations, the value of Young's modulus E for this material was found to be 2.53 ± 0.1 MPa.

4. Experimental results

Experimentally-determined values of the compression stiffness K are given in Table 1 for rubber layers bonded between two rigid cylinders and *in Table 2 for rubber layers bonded between two rigid spheres.* These results are plotted in Figure 3 in a reduced form; K/LE for layers of length L compressed between two rigid cylinders and K/DE for layers compressed between two spheres of diameter D, where E is Young's modulus; against the minimum separation h of the rigid members relative to their diameter D. Because of the wide range of values, logarithmic scales have been employed for both axes.

When the effects of outward bulging are ignored and only the stiffness component K_1 arising from simple compression is considered, equations 2 and 5 predict an inverse dependence of the reduced stiffness upon the ratio h/D, for relatively large separations. Such a dependence is represented by the broken linear relations in Figure 3, with a slope of -1: $K/LE = (4/3)\ (D/h)$ and $K/DE = (\pi/4)\ (D/h)$.

As can be seen in Tables 1 and 2, and Figure 3, the experimental results are in reasonably good agreement with the theoretical predictions. For layer thicknesses, denoted by the ratio h/D, smaller than about 1 the measured stiffnesses for layers between two rigid spheres tend to be somewhat lower than an inverse proportionality to h/D would suggest, in accordance with the full theory (lower full curve in Figure 3). Measured stiffnesses for layers between two rigid cylinders, on the other hand, tend to be somewhat higher at small thicknesses than an inverse proportionality to h/D would require, but again the actual dependence is predicted reasonably well by the full theory, at least for minimum separations h as small as about $0.1\ D$.

We conclude that the theoretical treatment, although including severe approximations, accounts satisfactorily for the stiffness of thin elastic layers bonded between two rigid parallel cylinders or between two rigid spheres, over a wide range of layer thickness extending down to one-tenth of the cylinder or sphere diameter and probably to still smaller thicknesses.

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Appendix

1. Calculation of stiffness component K_1 arising from simple compression.

(a) Layer between two parallel rigid cylinders.

A sketch of the deformed cross-section is shown in Figure 2. The compressive force dF_1 in an element of width dx and of unit length, located at a distance x from the center, is given by

$$dF_1 = 4E\delta\, dx/3h_x \qquad (A.1)$$

where

$$h_x = h + D(1 - \cos\theta) \qquad (A.2)$$

and

$$x = (D/2)\sin\theta. \qquad (A.3)$$

The effective value of the compression modulus has been taken as $4E/3$ in equation A.1 because, for relatively-long cylinders, the material undergoes only lateral displacements on compression. On substituting in equation A.1 for h_x and x from equations A.2 and A.3, and integrating between $\theta = -\pi/2$ and $\theta = +\pi/2$, the compressive force component F_1 per unit length is obtained as

$$3F_1/4E\delta = AI - \pi/2 \qquad (A.4)$$

where A and I are defined in equations 3 and 4.

(b) Layer between two rigid spheres.

In this case the compressive force dF_1 in an elementary ring of radius x and width dx is given by

$$dF_1 = 2\pi E\delta x \, dx/h_x \qquad (A.5)$$

where h_x and x are given in terms of the subtended angle θ (Figure 2) by equations A.2 and A.3. On integrating between $x = 0$ and $x = D/2$, the result given in equation 5 is obtained.

2. *Calculation of stiffness component* K_2 *and maximum pressure* P_m.

(a) Layer bonded between two parallel rigid cylinders.

The volume $x\delta$ displaced by compression of the material lying initially between vertical planes at $x = 0$ and $x = x$ is represented by a cross-hatched region in Figure 2. The outward bulge it gives rise to, assumed parabolic in shape, is represented by the second cross-hatched region, having a maximum lateral displacement k_x. If the material is incompressible in bulk, these two volumes are equal and hence

$$k_x = 3x\delta/2h_x \, . \qquad (A.6)$$

The pressure gradient necessary to maintain the parabolic displacement is given by (2):

$$dP/dx = -8Ek_X/3h_X^2 = -4E\delta x/h_X^3. \tag{A.7}$$

On integrating between the free surface lying at $x = D/2$ and $x = x$, the pressure at x is obtained as

$$P_X = (E\delta/2AD)/(A \sec\theta - 1)^2 \tag{A.8}$$

and the maximum hydrostatic pressure set up at $x = \theta = 0$ is then

$$P_m = E\delta/2AD(A - 1)^2. \tag{A.9}$$

A contribution to the normal force acting on the cylinders at $x = 0$ is also made by the simple compressive force treated in Appendix 1. It amounts to $4E\delta/3h$, from equation A.1.

The normal force F_2 per unit length associated with the pressure distribution P_X is obtained by integrating equation A.8 between $\theta = -\pi/2$ and $\theta = +\pi/2$:

$$F_2 = \int_{-\pi/2}^{+\pi/2} P_X \, dx, \tag{A.10}$$

yielding the result given in equation 6.

(b) Layer bonded between two rigid spheres.

In this case, conservation of volume on compression and the assumption of a parabolic displacement bulge, Figure 2, leads to

the following relation for the maximum lateral displacement $\underline{k_x}$

$$k_x = 3x\delta/4h_x \qquad (A.11)$$

in place of equation A.6. The corresponding pressure gradient is given by

$$dP/dx = -2E\delta x/h_x^3 \qquad (A.12)$$

in place of equation A.7. On integrating between the free surface at $\underline{x = D/2}$ and $\underline{x = x}$, the pressure at $\underline{x}$ is now obtained as

$$P_x = (E\delta/4AD)/(A \sec \theta - 1)^2 \qquad (A.13)$$

and the maximum hydrostatic pressure set up at $\underline{x = \theta = 0}$ is

$$P_m = E\delta/4AD(A - 1)^2. \qquad (A.14)$$

The normal force $\underline{F_2}$, arising from the pressure distribution $\underline{P_x}$, is given by integrating equation A.13 over the bonded surface, yielding the result given in equation 8. Again, an additional contribution to the normal stress at $\underline{x = 0}$ is made by the simple compression term treated in Appendix 1. It amounts to $\underline{E\delta/h}$.

Table 1: Compression stiffness *K* for rubber layers of various minimum thickness *h*, bonded between two parallel rigid cylinders of diameter *D* = 19.0 mm and of length *L* = 127 mm.

h (mm)	*K* (expt.) (MN/m)	*K/LE* (expt.)	*K/LE* (calc.)
1.975	7.70	23.95	19.15
1.985	5.60	17.45	19.05
4.00	2.10	6.54	7.55
4.05	1.98	6.16	7.40
7.30	1.11	3.46	4.05
7.90	0.85	2.645	3.30
15.65	0.365	1.135	1.55

Table 2: Compression stiffness K for rubber layers of various minimum thickness h, bonded between two rigid spheres of diameter D = 41.7 mm.

h (mm)	K (expt.) (kN/m)	K/DE (expt.)	K/DE (calc.)
2.67	760	7.20	7.10
2.88	538	5.10	6.63
3.13	635	6.02	6.15
5.85	380	3.60	3.52
9.15	268	2.54	2.38
9.80	210	1.99	2.24
13.45	169	1.60	1.71
21.6	98	0.929	1.135
28.1	101	0.957	0.905

Figure Captions

Figure 1. Rubber layer (cross-hatched) bonded between (a) two rigid spheres and (b) two rigid parallel cylinders.

Figure 2. Sketch of a half-section of a compressed layer, showing the volume between $x = 0$ and x that is displaced by compression and the maximum lateral displacement k_x of the plane initially at x.

Figure 3. Experimental measurements of compression stiffness K for rubber layers bonded between two rigid parallel cylinders (open circles) and between two rigid spheres (filled-in circles) plotted against the minimum thickness h relative to the diameter D of the cylinders or spheres. The full curves represent the theoretical predictions; equations 2 and 6 for cylinders and equations 5 and 8 for spheres. The broken curves represent the theoretical predictions when the separation h/D is relatively large and the restraints at the bonded surfaces become unimportant.

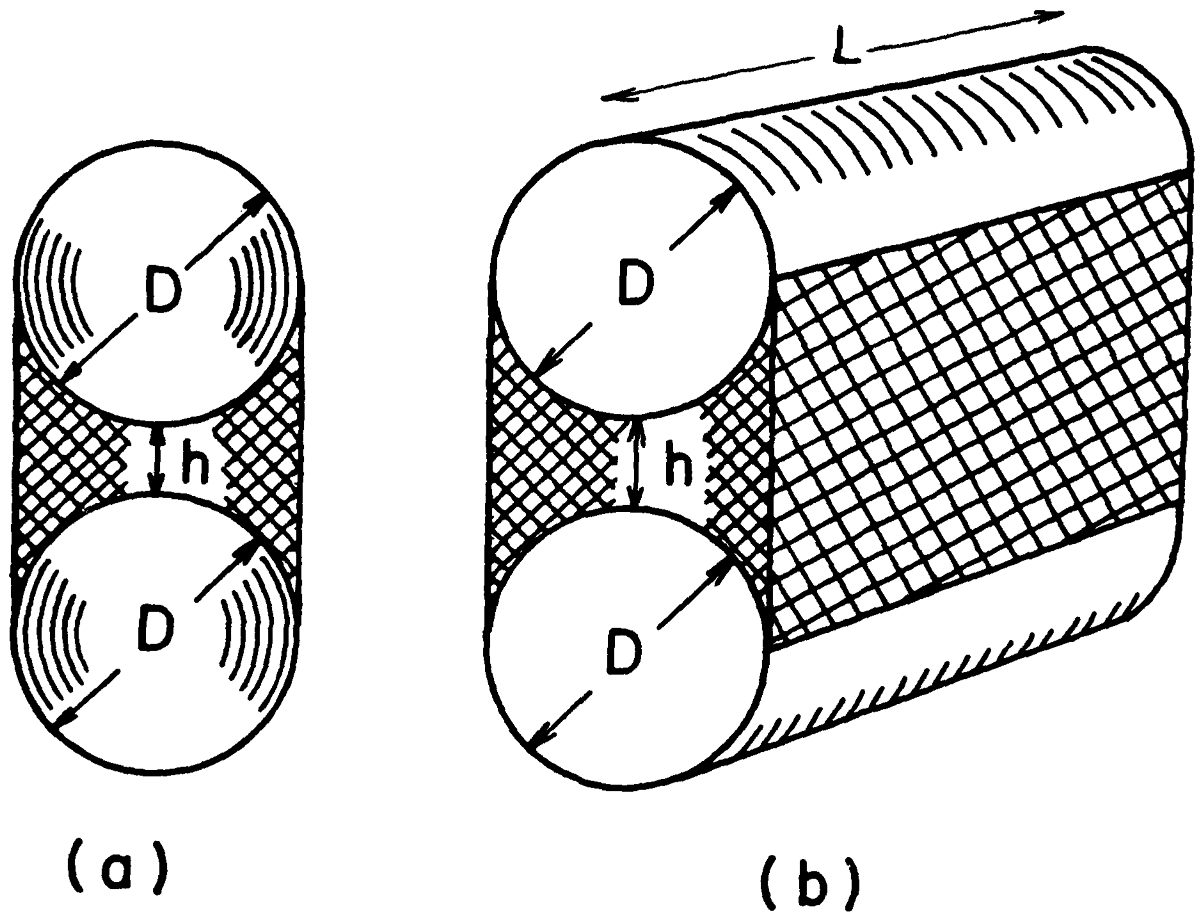


Figure 1

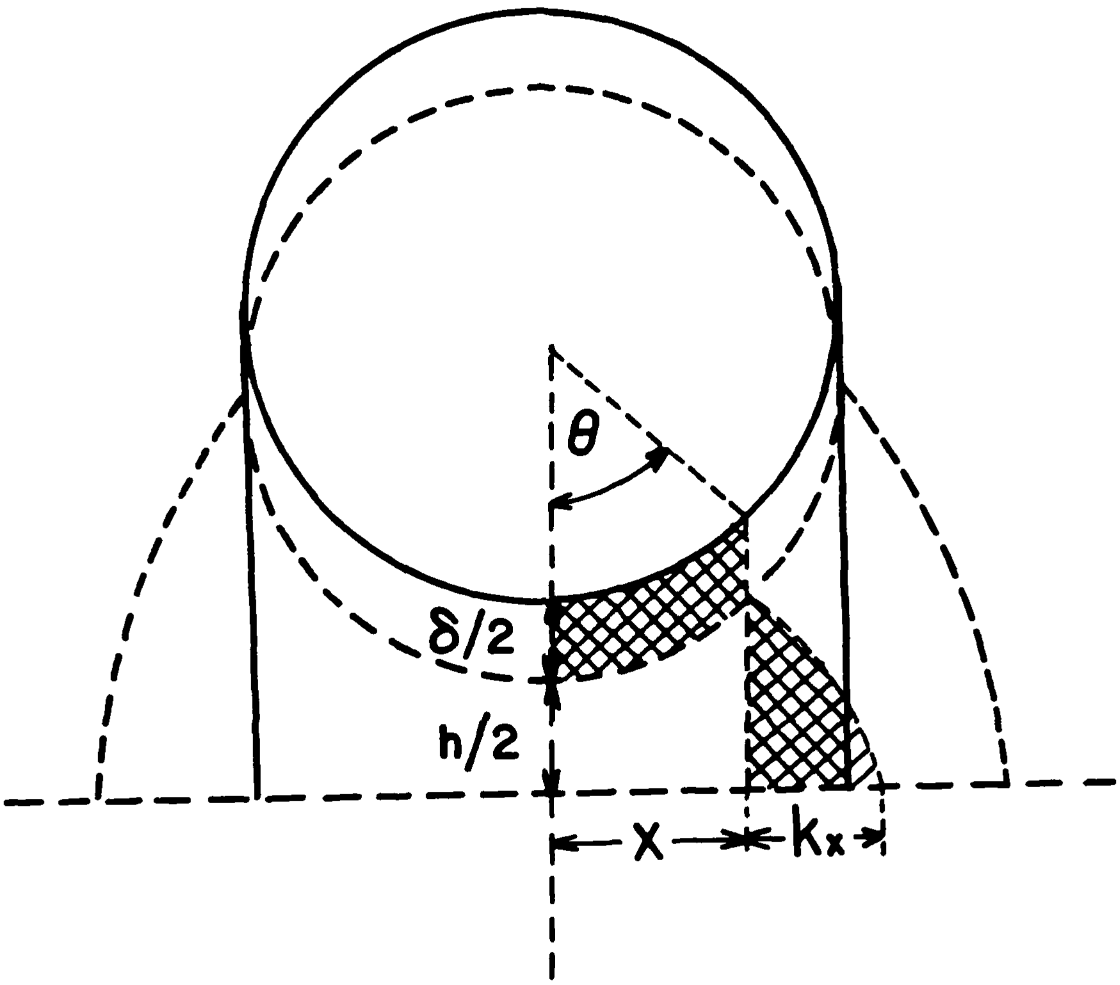
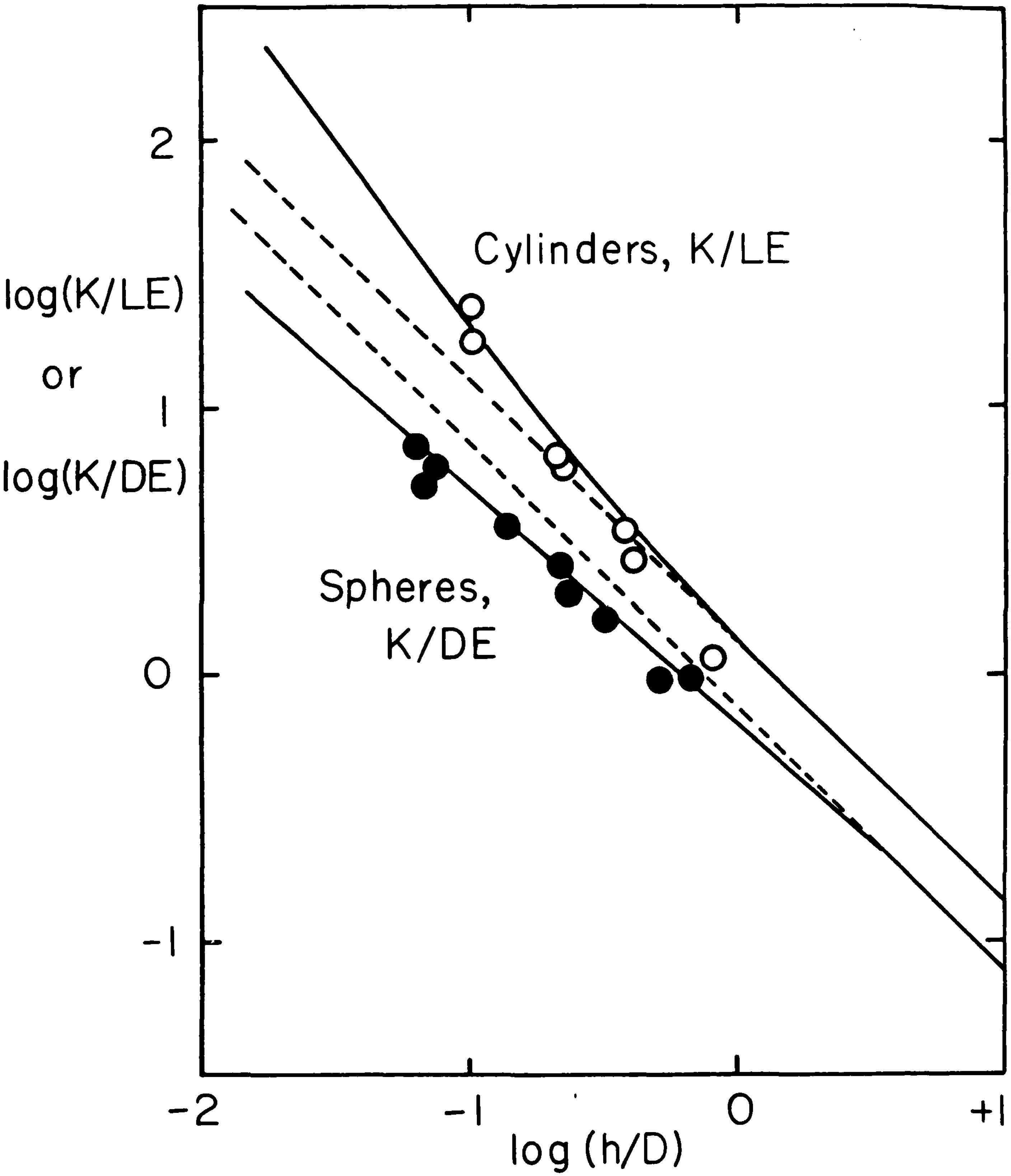


Figure 2



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